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Minimising Energy Use in Milk Powder Production using Process Integration Techniques

Martin J. Atkins[a*], Michael R.W. Walmsley[a], Timothy G. Walmsley[a],
Zsófia Fodor[b], James R. Neale[a]

[a] Univ. of Waikato, Energy Research Centre, School of Engineering, Hamilton, New Zealand
[b] Centre for Process Integration and Intensification – CPI^2, Univ. of Pannonia, Veszprém, Hungary
matkins@waikato.ac.nz

Spray drying of milk powder is an energy intensive process and there remains a significant opportunity to reduce energy consumption by applying process integration principles. The ability to optimally integrate the drying process with the other processing steps has the potential to improve the overall efficiency of the entire process, especially when exhaust heat recovery is considered. However, achieving the minimum energy targets established using pinch analysis results in heat exchanger networks that, while theoretically feasible, are impracticable, unrealistic, contain large number of units, and ultimately uneconomic. Integration schemes that are acceptable from an operational point of view are examined in this paper. The use of evaporated water is an important factor to achieve both energy and water reductions. The economics of additional heat recovery seem favourable and exhaust heat recovery is economically justifiable on its own merits, although milk powder deposition should be minimised by selecting an appropriate target temperature for the exhaust air. This will restrict the amount of heat recovery but minimise operational risk from heat exchanger fouling. The thermodynamic constraints caused by the operating temperatures of the dryer and the poor economics exclude the use of heat pumps for exhaust heat recovery in the short to medium term.

1. Introduction

Spray drying is used to produce a variety of products from milk powder to speciality chemicals and is an energy intensive process (Baker and McKenzie, 2005). Most milk powder spray dryers have little or no heat integration within the dryer itself; although there may be a high level of zonal integration in the prior processing steps namely milk treatment/pasteurisation and evaporation. While there remains a significant opportunity to reduce energy consumption by recovering heat from the spray dryer exhaust, there is no standard method for integrating the evaporators and the dryer. There has been mixed success with heat recovery from milk spray dryer exhausts (Reay, 1980; Miller, 1987;). When one examines industrial spray dryers there exists many different methods of recovering heat and how the water removed during the evaporation stages (commonly called cow water) is used is an important factor on both the total energy and fresh water usage of the plant. Energy and water use varies markedly with ranges of reported specific energy content for milk powder ranging from 4.6 GJ/t to 221.4 GJ/t of powder (Xu and Flapper, 2011). Water usage for milk powder ranges from 0.07 m^3_{water}/m^3_{milk} to 2.70 m^3_{water}/m^3_{milk} (Prasad et al., 2004).
The ability to optimally integrate the drying process with the other processing steps has the potential to improve the overall efficiency of the entire process, especially when exhaust heat recovery is considered (Atkins et al., 2011). However, achieving the minimum energy targets established using

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pinch analysis results in heat exchanger networks that, while theoretically feasible, are impracticable, unrealistic, contain large number of units, and ultimately uneconomic. This paper will examine practical heat exchanger networks to minimise dryer energy usage including the option of dryer exhaust heat recovery. Critical stream matches are identified to minimise energy usage and capital cost estimates will be calculated. The feasibility and economics of integrating heat pumps is also briefly discussed.

2. Industrial Milk Powder Spray Dryer

A characteristic industrial milk powder production plant is illustrated in Figure 1 with three distinct zones, milk treatment, evaporation, and multi-stage spray drying. A typical heat exchanger network is also shown and it is important to note that there is no integration for the spray dryer and no heat recovery. There are multiple variations on this plant layout and there appears to be no standard heat recovery scheme. Some plants use hot cow water as a preheat for the main dryer inlet air instead of preheating standard milk although there is no direct energy benefit from this use of cow water.

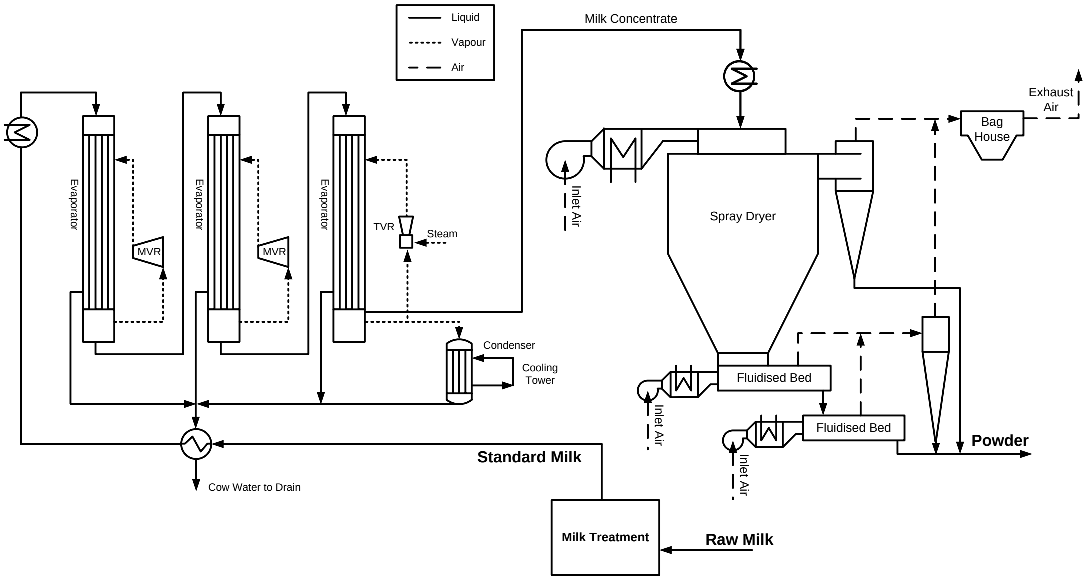

Figure 1. Simplified flow sheet for current milk powder plant including integration

The process stream data for the plant is shown in Table 1. The nominal production capacity is 23.5 t/h of powder. The target temperatures for the cow water streams are indicated as soft data (meaning they are not fixed) by an *. The cow water is eventually discharged to drain and it needs to be discharged below a temperature of 30 °C. There is also the option to reuse cow water as a first rinse as part of the Clean-In-Place (CIP) regime. A ΔT_{min} contribution method was used with liquid streams given a $\Delta T_{min.cont}$ = 2.5 °C, air streams a $\Delta T_{min.cont}$ = 10 °C, and vapour streams a $\Delta T_{min.cont}$ = 1 °C. The individual evaporator effects have not been included as they are already well integrated and effects 1 and 2 use Mechanical Vapour Recompression (MVR) and effect 3 uses Thermal Vapour Recompression (TVR) to upgrade the temperature of the vapour. Several variations of this configuration are also common. The operating temperatures and pressures of the effects are usually fixed and cannot be altered as there exists a relatively small range of temperatures and pressures that evaporators may operate at due to the thermal sensitivity of the product and operability of the equipment. As a result there is seldom opportunity to alter the thermodynamic profile of evaporators to improve integration with the background process, especially in retrofit situations.

The Grand Composite Curve (GCC) for the stream data above is illustrated on the left in Figure 2. The hot and cold utility targets are 24.4 MW and 1.7 MW respectively. The cooling demand is due to cooling the cream B and skim milk streams down to 8 °C in milk treatment. Milk treatment zones tend to have high levels of heat recovery and small approach temperatures (3 – 5 °C) and therefore integration exclusively within this zone is practical and economic. The exhaust air stream has been given a target temperature of 55 °C and although this could be lower and more heat could be recovered, there is a major issue of milk powder deposition on the heat exchanger to overcome. To minimise fouling and maximise dryer run time between washes a limit of 55 °C was chosen.

*Table 1. Stream data for the example dryer A. Soft data is indicated by an *.*

Stream Name	Zone	T_s °C	T_t °C	mc_p kW/°C	ΔH kW
Raw Milk	Milk Treatment	8	46	352.9	13,410.2
Skim Milk	Milk Treatment	46	8	313.6	11,916.8
Cream A	Milk Treatment	46	85	32.6	1,271.4
Cream B	Milk Treatment	85	8	32.6	2,510.2
Standard Milk	Evaporation	8	70	278.4	17,260.8
Effect 1 Cow Water	Evaporation	67.5	25 - 13*	145.5	7,929.8
Effect 2 Cow Water	Evaporation	61	25 - 13*	85.7	4,113.6
Effect 3 Cow Water	Evaporation	53.9	25 - 13*	13.0	531.7
Effect 1 Condenser	Evaporation	54	53.9	-	2,460.0
Milk Concentrate	Dryer	54	65	38.1	419.1
Main Dryer Air	Dryer	20	200	120.5	21,690.0
Well Mixed Air Inlet	Dryer	20	50	10.2	306.0
VF1 Air Inlet	Dryer	20	45	14.9	372.5
Main Air Exhaust	Dryer	78	55	167.9	3,861.7
CIP Water	Site	15	55	32.0	1,280.0

The psychrometric chart is illustrated on the right in Figure 2 and indicates the path of the dryer air and also the potential for heat recovery from the exhaust air stream (T_{exh} to T_{DP}). T_{exh} is the outlet dryer temperature (78 °C) and the dew point (T_{DP}) is 39 °C in this case. An adjusted sticky curve for pure lactose and a velocity of 4 m/s is also shown in the figure. Lactose is a major component in milk powder and represents the worst case scenario for stickiness. At an outlet temperature of 55 °C the exhaust heat exchanger should avoid major deposition problems and is a good trade-off between heat recovery and operational risk.

The minimum energy heat exchanger networks for the milk powder plant result in multiple stream splits on streams such as inlet air streams that are non-practical to split. Cyclic matching can overcome some of this but it results in many additional heat exchangers and costly pipework. Furthermore some of the streams are not suitably matched and are geographically isolated. For example the well mixed air inlet and VF1 air inlet are both geographically isolated and both have fairly small heating duties. The outlet temperatures of these streams also require strict control and so it is practical to let these be heated completely with hot utility. The marginal energy penalty is relatively small.

3. Economic Modelling and Practical Networks

Supertarget software from KBC was used to perform the pinch analysis and to design the several heat exchanger networks. The energy targets and actual energy use for different practical networks was assessed as well as altering the target temperature of the cow water. The data for the individual heat exchangers was used to perform a UA analysis. One drawback of all the available commercial pinch software is the limitations for heat exchanger area calculation when different types are heat exchangers are desired. The UA analysis was then used as a platform for further economic analysis. The parameters for the economic analysis is given in Table 2.

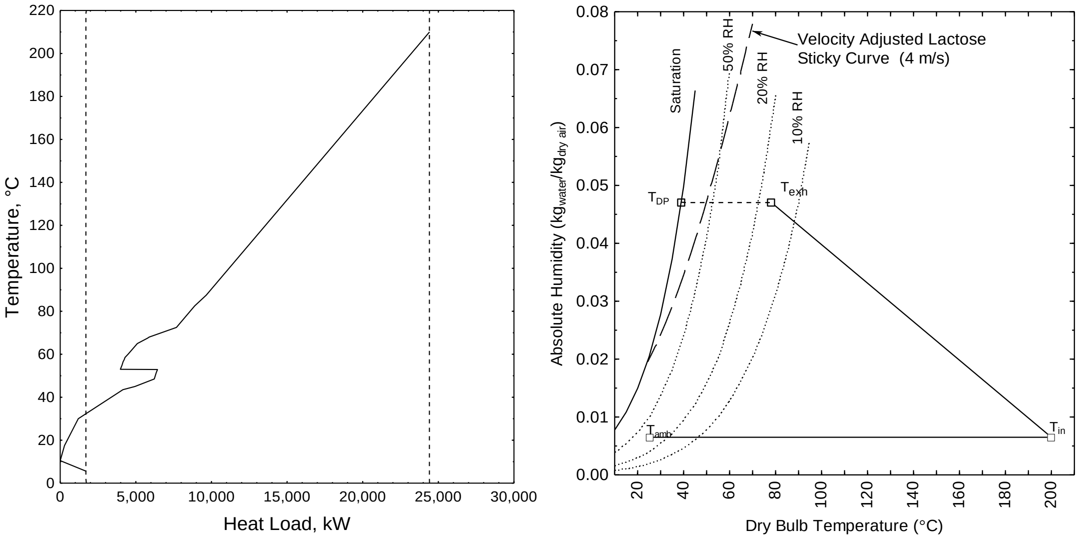

Figure 2. Grand composite curve for the powder plant (Q_{hot} = 24,417 kW, Q_{cold} = 1731 kW) (left) and a psychrometric chart showing dryer air with heat recovery and velocity adjusted lactose sticky line (4 m/s) (right).

Table 2. Parameters used for the economic analysis

Cost Parameter	Cost or Cost Function
Operating Hours	6000 hr/yr
Steam Cost	$0.045 kWh
	$270/kW.yr
Finned Tube HX	$2140A^{0.815}$
Plate-Frame HX	5(270A+4000)

The use of a UA analysis was useful for comparing the relative merits of different schemes when the same type of heat exchangers are used; however in this case an analysis of the major increase in UA for the different schemes is caused by the three cow water/standard milk heat exchangers and not by the exhaust heat exchanger as one might first think. These would be gasket plate-frame heat exchangers and have a far greater overall heat transfer coefficient than the finned tube type used for exhaust heat recovery. Capital costing estimates were made for exhaust heat exchangers and the remaining plate heat exchangers using suitable cost functions and an overall U of 40 W/m^2.°C and 2000 W/m^{2}°C respectively. A total annualised cost was calculated by annualising the capital cost (based on a 10 % interest rate and a 10 y plant life) and added it to the annual energy cost. This gives a much better picture than the simple payback criteria as the “best” option is somewhat different if a total annualised cost is used.

A simplified flow sheet of the best economic scheme is illustrated in Figure 3 and shows the cow water preheating the standard milk and being cooled to 13 °C. The cow water from each effect is matched separately to best use the temperature of the effects. The cold cow water is then used as a heat sink for the TVR condenser before being used to pre-heat the CIP water (HX not shown). After the CIP water preheat the temperature of the cow water is 35 °C and can be stored to be used as a first warm CIP rinse. The summary of the energy use, energy savings, UA analysis, and economic analysis is given in Table 3. Based on the total annualised cost exhaust heat recovery along with using the cow water multiple times is the most economic option and yields a saving of 7.2 MW. The total Q_{hot} required is only 1.9 MW off the target and the resultant network is both acceptable from and operational point of view it also yields reduction in water use by removing a cooling tower and reducing CIP water usage. The excess cold cow water that is not used in the condenser can receive additional treatment to make it acceptable for other uses around the plant further displacing freshwater use.

Milk treatment is well integrated and the heat exchanger network is not shown in Figure 3. Based on the economic analysis exhaust heat recovery is justifiable on its own merits and could be implemented separately from the cow water heat exchangers.

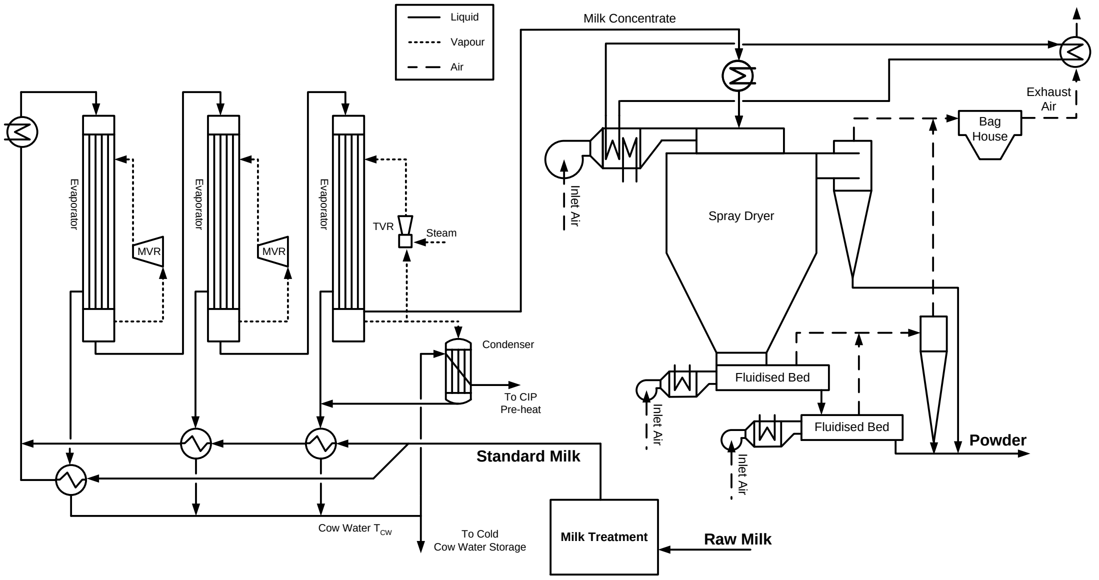

Figure 3. Flow sheet for best option (Ex-CW 13°)

4. Heat Pumps

The use of a heat pump has been proposed to recover and upgrade some of the latent heat from the dryer exhaust and from the GCC of the dryer alone it is obvious that this would be beneficial. However once the actual temperatures are considered and the options for refrigerants are examined there are challenges finding a suitable refrigerant that will be operationally acceptable and give an economic Coefficient of Performance (COP) (Wang et al., 2010; Wang and Cleland, 2011). Typical ratios of the cost of thermal energy to electrical energy are around 3 and therefore the COP for an acceptable heat pump would have to be above 3 to justify the additional operational cost. A transcritical cycle using R134a looks to hold the most promise with around 50 % of the inlet air heating duty being able to be delivered at a COP of around 3.85. However once the operating costs are factored in, there is only around a 20 % saving in the cost of heating the inlet air, which is only marginally better than a simple exhaust heat exchanger recovery part of the sensible heat and avoiding conditions with high powder disposition (Wang and Cleland, 2011). The issue of powder deposition would be greatly exacerbated if the latent heat was also recovered and as a result of the unfavorable economics it seems unlikely that heat pumps will be used for milk powder spray dryers. The capital cost of large industrial heat pumps is also prohibitive and the process risk is extremely high. Due to these factors it seems unlikely that heat pumps will be applied to milk powder spray dryers in the immediate future.

Table 3. Summary of savings for different schemes (Target Q_{hot}=24,417 kW).

Scheme	Q_{hot} kW	Savings kW	HX No.	Total UA kW/°C	Total Capital Cost/Savings $/kW	Simple Payback yr	Total Annualised Cost $/yr
Current	33,496.5	-	15	3,571.7	-		9,044,055
CW 13°C	30,161.9	3,343.6	18	4,541.2	285.30	1.06	8,578,095
CW 20°C	31,464.4	2,032.1	19	3,994.6	250.16	0.93	8,298,498
Ex-CW 13°C	26,300.2	7,196.3	20	4,650.8	346.20	1.28	7,506,397
Ex-CW 18°C	27,187.1	6,309.4	20	4,173.2	343.43	1.27	7,693,064
Ex-CW 20°C	27,602.7	5,893.8	20	4,001.0	347.54	1.29	7,785,994
Ex-CW 22°C	28,088.8	5,407.7	20	3,877.3	362.83	1.34	7,903,202
Ex-CW 25°C	28,821.9	4,674.6	20	3,745.6	399.63	1.48	8,085,851
Exhaust Only	29,634.8	3,861.7	16	3,681.3	398.79	1.48	8,251,955

5. Conclusion

Some of the practical issues of integrating a milk powder spray dryer have been discussed and the additional cost and operational risk of having a minimum energy network does not justify meeting the targets. However through prudent use of the cow water as both a heat source and heat sink at various times can significantly reduce the energy requirement and get within 93% of the target. The economics of additional heat recovery seem favourable and exhaust heat recovery is economically justifiable on its own merits, although milk powder deposition should be minimised by selecting an appropriate target temperature for the exhaust air. This will restrict the amount of heat recovery but minimise operational risk from heat exchanger fouling. The thermodynamic constraints caused by the operating temperatures of the dryer and the poor economics exclude the use of heat pumps for exhaust heat recovery in the short to medium term.

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